Chapter 4

Bio-Optical Measurements in Upwelling Ecosystems in Support of SIMBIOS

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4.1 INTRODUCTION

The upwelling region of the equatorial Pacific Ocean, which spans one quarter of the earth's circumference, strongly impacts global biogeochemistry. This upwelling system has significant implications for global CO_2 fluxes (Tans *et al.*, 1990; Takahashi *et al.*, 1997; Feely *et al.*, 1999), as well as primary and secondary production (Chavez and Barber, 1987; Chavez and Toggweiler, 1995; Chavez *et al.*, 1996; Dugdale and Wilkerson, 1998; Chavez *et al.*, 1999; Strutton and Chavez, 2000). In addition, the region represents a vast oceanic (case 1) region over which validation data for SeaWiFS are needed. This project consists of an optical mooring program and cruise-based measurements focused on measuring biological and chemical variability in the equatorial Pacific and obtaining validation data for SeaWiFS. Since 1996, the MBARI equatorial Pacific program has demonstrated ability to:

1. obtain high quality, near real time measurements of ocean color from moored platforms in the equatorial Pacific.
2. process and quality control these data into files of the required format for the SeaBASS database.
3. obtain robust ship-based optical profiles and pigment concentration measurements, also for submission to SeaBASS.
4. process and interpret the time series, satellite and ship-based data in order to quantify the biogeochemical processes occurring in the equatorial Pacific on time scales of days to years (Chavez *et al.*, 1998; Chavez *et al.*, 1999; Strutton & Chavez, 2000; Strutton *et al.*, 2001, Ryan *et al.*, 2002).

4.2 RESEARCH ACTIVITIES

Moorings

The arrangement of the moored MBARI bio-optical and chemical instruments positioned at 0°, 155°W and 2°S, 170°W has previously been described (Chavez *et al.* 1998, Chavez *et al.* 1999, McClain and Fargion 1999). The moorings are two of ~70 which form the Tropical Atmosphere Ocean (TAO) array. From these locations, daily local 10 am and noon (approximate time of MODIS and SeaWiFS overpasses, respectively) bio-optical and chemical data are transmitted via service ARGOS in near real time to MBARI, and then presented on the internet at: http://bog.shore.mbari.org/~bog/oasis.html.

Higher frequency, publication-quality data (15-minute intervals) are also recovered at approximately six month intervals, and sent to the SeaBASS database after thorough quality control. Derived products, such as water leaving radiance (L_w), and remote sensing reflectance (Rrs) are incorporated into these data files for validation efforts. In previous years, L_w has been determined through three different methods (McLain and Fargion, 1999b), but L_w is now computed only as follows. The diffuse attenuation coefficient (K_λ) throughout the upper 20m of the water column is calculated using Ed_{3m+} and Ed_{20m-} Then, using this K_λ, Lu_{20m} is extrapolated back to just below the surface (Lu_{0m-}) and multiplied by 0.544 (a scaling factor that considers the transmission of light across the air-sea interface) to obtain Lu_{0m+}. Of the three methods previously used, this has been shown to be the most reliable, primarily because the 3m+ and 20m-instruments are less susceptible to fouling. With the addition of a 10 m hyperspectral radiometer, the efficacy of this method can now be assessed.

During 2003 our data processing, quality control and data provision capabilities have improved. The following quality control procedures are currently employed:

1. Measured surface-incident irradiance (E_s) can not be greater than 1.15 times modeled, clear-sky E_s (Frouin, 1989).
2. K_λ must be greater than that of pure water (Morel, 1988).
3. OC4V4 chlorophyll is computed for the Rrs ratios of 412/555, 443/555, 490/555, and 510/555 and the coefficient of variance is determined for each wavelength combination. Coefficients of variance greater than 0.4 are not acceptable.
4. Time series of all parameters at all wavelengths for all individual instrument deployments are plotted together as one long time series to identify discontinuities between deployments, due to problems such as vandalism, fouling and calibration issues. Normalizing specific wavelengths against others is also used to identify discontinuities.

With the buoy design and data collection methods now verified in the field, we are making significant advancements to the quantity and quality of optical data collected during this funding period. In October 2002, HOBILabs HR3 hyperspectral radiometers were deployed at 10m on both equatorial Pacific moorings (0° 155°W and 2°S 170°W) to supplement the discrete wavelengths measured at 20 m. These configuration changes yielded data of significantly higher quality for almost the same cost as the existing discrete-wavelength instruments. These instruments were retrieved in June 2003 (new HR3 units were subsequently deployed after recovery) providing hyperspectral data consisting of:

- downwelling irradiance above the surface (3m)
- downwelling irradiance and upwelling radiance at 10m depth.

The Hydrorad data are available in programmable bin sizes (highest resolution 0.37nm), over the range ~300 to 850nm, but for deployment in the equatorial Pacific we have binned the data to ~2nm resolution. We also successfully recovered and deployed HOBILabs Hydroscat 2 (HS2) instruments fitted with new copper anti-fouling shutters. The HS2 measures backscatter and fluorescence at two wavelengths (490 and 676 nm). With the deployment of these new instruments, particularly the hyperspectral radiometers, we have been able to submit optical data beyond our initial deliverables as stated in the SIMBIOS grant, and can better support recent and forthcoming ocean color missions such as MODIS and GLI and the development of ocean color algorithms that will go beyond chlorophyll.

Optical profiling measurements

On mooring maintenance cruises, optical profiles of the euphotic zone are performed daily, when possible, close to local noon using a Satlantic SeaWiFS Profiling Multispectral Radiometer (SPMR). Profile data are processed using Satlantic's ProSoft software, and a suite of derived products, including diffuse attenuation coefficients, water leaving radiances (L_{wn}) and light penetration depths are obtained. Products of interest (mostly L_{wn}) are provided to NASA post-cruise, and the profile data are archived at MBARI along with existing optical profiles from almost every oceanic region.

In situ measurements

Table 4.1 recaps the cruises embarked on by MBARI this fiscal year in support of SIMBIOS. The cruise-based measurements consist primarily of fluorometric chlorophyll (Chavez *et al.* 1995) & nutrient profiles (8 depths, 0-200m) obtained at CTD stations between 8°N and 8°S across the Pacific from 95°W to 165°E. Latitude-depth sections of shipboard data can now be viewed at:http://www.mbari.org/~ryjo/tropac/sections

On mooring maintenance cruises (the 155°W and 170°W meridional transects), HPLC samples are collected and productivity (^{14}C, ^{15}N) measurements are also performed. These data are stored at MBARI and the pigment data supplied to the SeaBASS database for algorithm development. Figure 4.1 shows a regression comparison, with good agreement between shipboard measurements and HPLC analysis of chlorophyll *a*. The HPLC analysis was conducted by the Center for Hydor-Optics and Remote Sensing (CHORS).

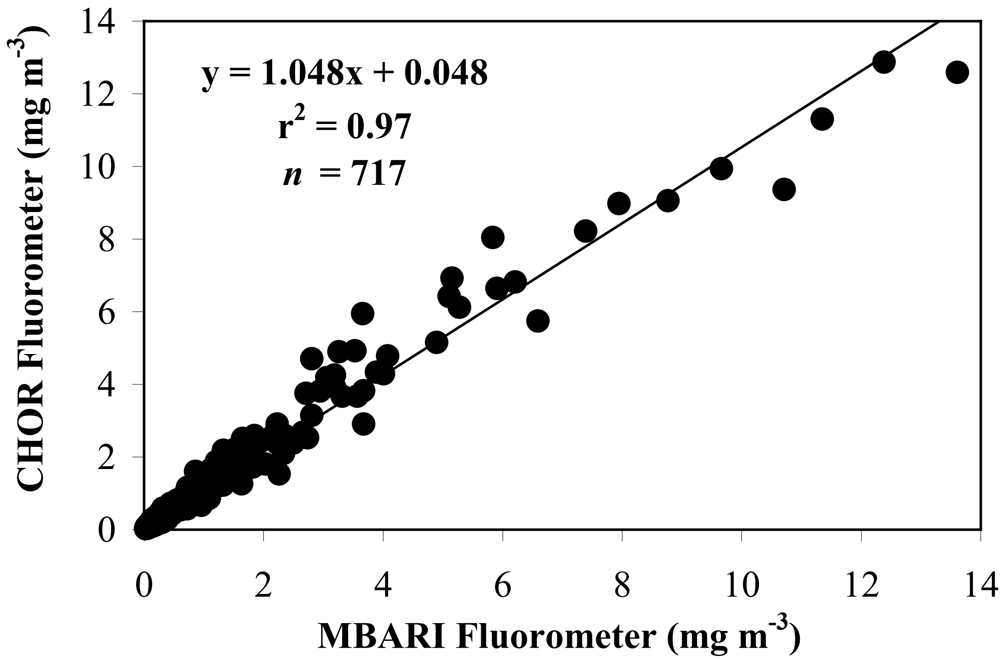

Figure 4.1: Regression model comparing *in situ* Chlorophyll *a* determined by a Turner fluorometer at sea versus chlorophyll determined by HPLC at the Center of Hydro-Optics and Remote Sensing (CHORS). Samples were collected from both the equatorial Pacific and Monterey Bay.

4.3 RESULTS

Biogeochemical cycles

Several publications describing ecosystem variability in the equatorial Pacific have been produced under MBARI's SIMBIOS funding. Chavez *et al.* (1998) used mooring data from 0°, 155°W to describe the biological-physical coupling observed in the central equatorial Pacific during the start of the 1997-98 El Niño. Chavez *et al*. (1999) combined the physical, biological and chemical data from moorings, ships and SeaWiFS to provide a complete picture of the ecosystem's reaction to the intense physical forcings that occurred during the 1997-98 El Niño. Strutton and Chavez (2000) summarized the *in situ* cruise measurements spanning the period from November 1996 to December 1998, and used these data to describe the perturbations to chlorophyll, nutrients and productivity during the same time period. Strutton *et al*. (2001) used time series from smaller Satlantic bio-optical packages and SeaWiFS imagery to detail the extreme anomalies in chlorophyll related to the passage of tropical instability waves (TIWs) during the latter half of 1998 and 1999. These data not only documented the magnitude of the observed chlorophyll variability, but also shed light on the mechanisms possibly responsible for the concentration of chlorophyll in connection with TIWs. Ryan *et al*. (2002) thoroughly described and explained the intense and widespread blooms that dominated the equatorial Pacific during the 1998 La Niña.

Chavez *et al*. (2000) documented the design, and demonstrated the effectiveness of a shutter mechanism that prevents bio-fouling of the *in situ* radiometers on the moorings. Kuwahara *et al*. (2003) contributed to the 4th revision of the Ocean Optics Protocols series with a chapter titled, "Radiometric and Bio-optical Measurements from Moored and Drifting Buoys: Measurement and Data Analysis Protocols".

Other manuscripts currently in press/preparation include a chapter in Seuront and Strutton (Eds): ‘Handbook of scaling methods in aquatic ecology: Measurements, analysis, simulation’ (CRC Press, publication October 2003), a manuscript describing the biological component of the equatorial Pacific heat budget (Strutton and Chavez, in press), and a paper that analyzes the time series of optical data collected at the mooring location (Kuwahara *et al*.)

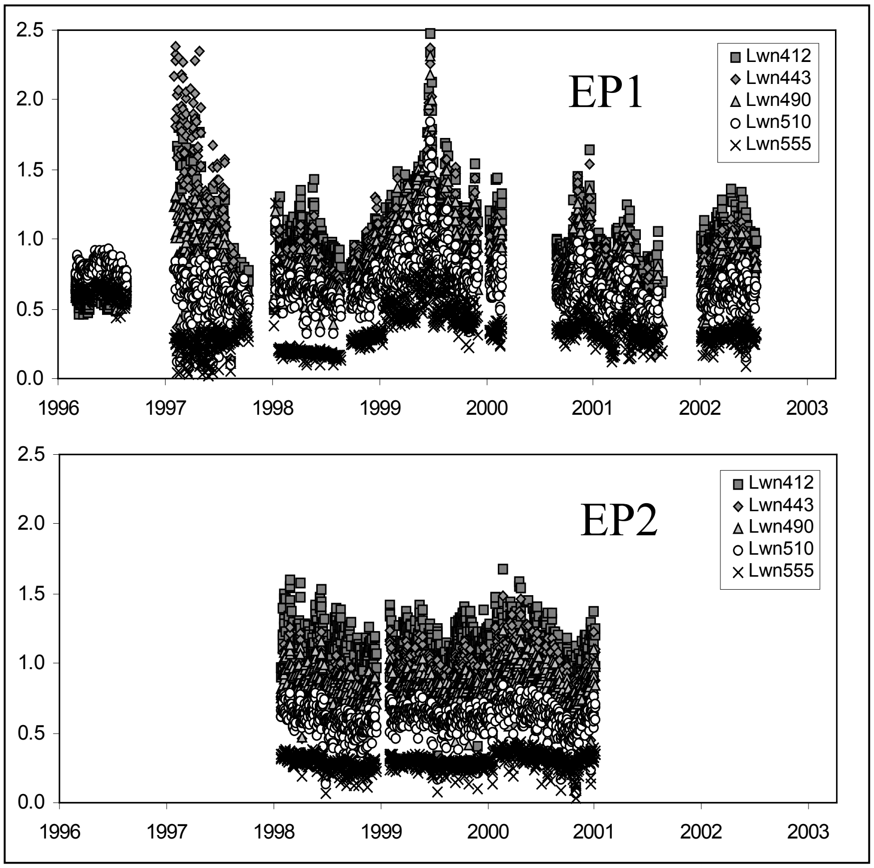

Figure 4.2: The time series (December 11,1996 – June 18, 2003) of normalized water-leaving radiance, L_{wn} [$\mu W\ cm^{-2}\ nm^{-1}\ sr^{-1}$], derived from the L_u and K_d data obtained from MBARI optical instruments on the TAO moorings at 0° 155°W (EP1) and 2°S 170°W (EP2). The data have been subject to quality control as described in the methods.

SeaWiFS Calibration/Validation

At the present time, we are concentrating on refining our data analysis and quality control protocols of the full mooring records (1996-2003) for both moorings in combination with the newly reprocessed SeaWiFS data. Analysis and improvements to quality control methods continue on the reprocessed data. These data have been uploaded to SeaBASS. Figure 4.2 shows our most recent update of the time series of L_{wn}. Note: L_{wn} collected from the upwelling region is more variable than data collected from EP2, which is less susceptible to upwelling.

McClain and Fargion (1999b) showed matchup data derived from optical profiles of the SPMR in the equatorial Pacific. The mooring data collected at EP1 (excluding the anomalous El Nino year) indicated good agreement between the satellite- and profile-derived water-leaving radiance values (Figure 4.3). Similarly, Figure 4.4 compares the surface chlorophyll values obtained from SPMR casts with the extracted chlorophyll samples obtained at the same location.

In addition to our deliverables, the mooring data collected at EP1 during 2002 yielded hyperspectral E_d data (Figure 4.5) and backscattering data, namely $b_b(490)$ and $b_b(676)$ (Figure 4.6).

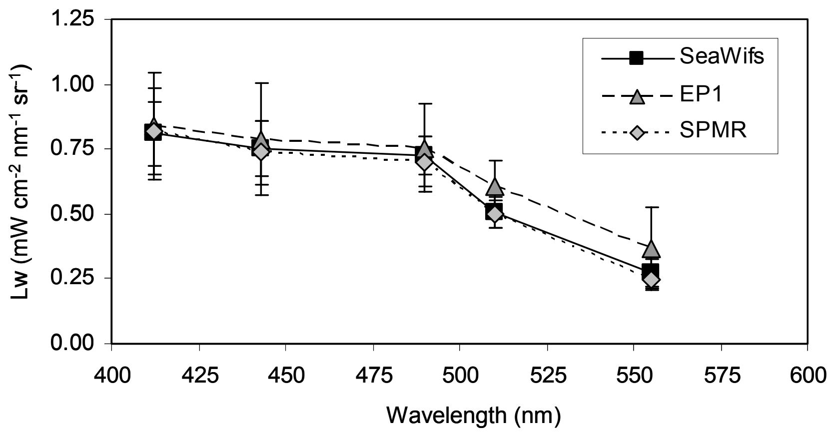

Figure 4.3: Water leaving radiance matchups between SeaWiFS, EP1 (0, 155W) optical mooring, and SPMR profiles (where available) from June 1998 to Oct 2001. Anomalous data collected during the 1997 – 1998 El Nino period were not included. The number of matching points between SeaWiFS and the optical mooring at 412, 443, 490, 510, and 555 nm were, n = 245, 238, 236, 208 and 210, respectively. For SPMR profiles conducted at the mooring location, n = 10.

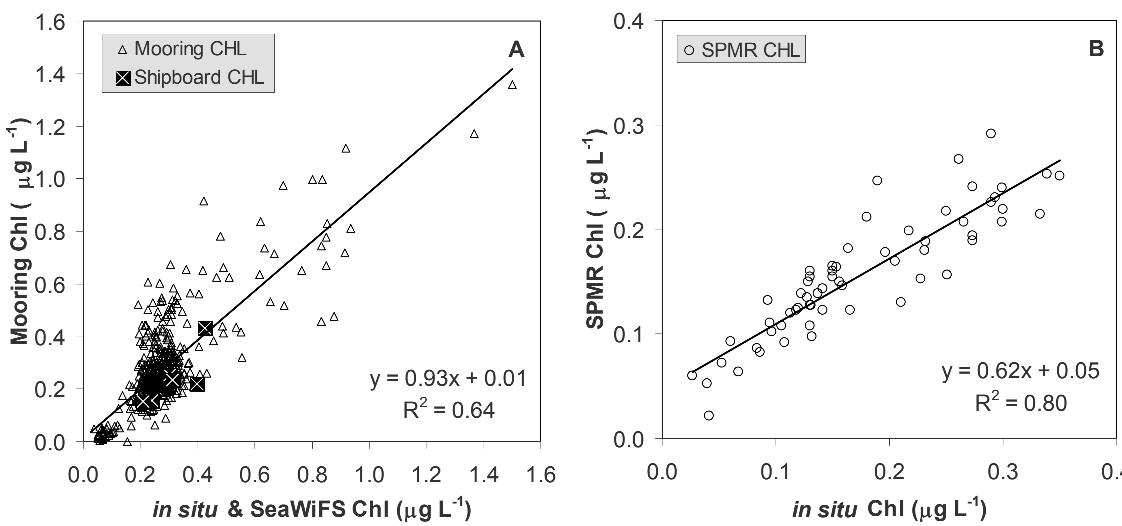

Figure 4.4: (A) Comparison of SeaWiFS and shipboard *in situ* chlorophyll with mooring-derived chlorophyll for the MBARI instruments at 0° 155°W (EP1). Mooring-derived chlorophyll was calculated using an algorithm by Morel (1988). Regression analysis for SeaWiFS vs. Mooring Chl is also shown. (B) Comparison of chlorophyll from shipboard water samples with chlorophyll calculated from SPMR casts. SPMR chlorophyll is calculated using OC4V4 algorithm by O'Reilly (2001) applied to normalized water-leaving radiance from the SPMR. All data have been subject to quality control.

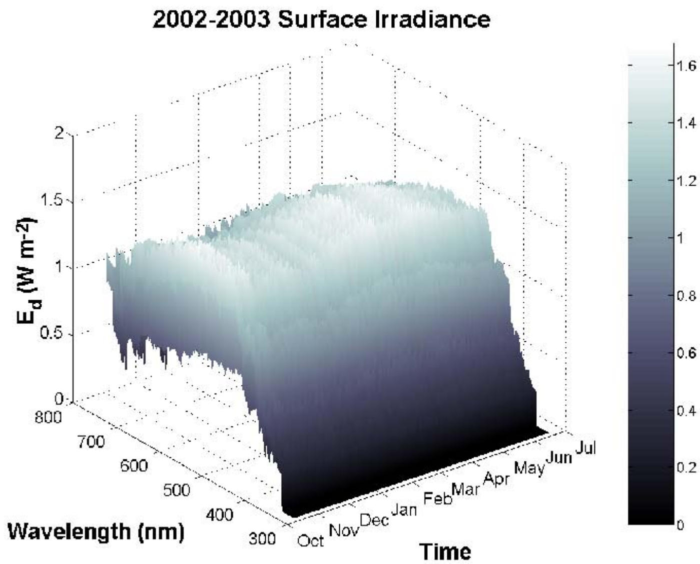

Figure 4.5: Time series of hyperspectral downwelling irradiance at EP1. Data of this kind could be used in further algorithm development or as validation data for future ocean color missions.

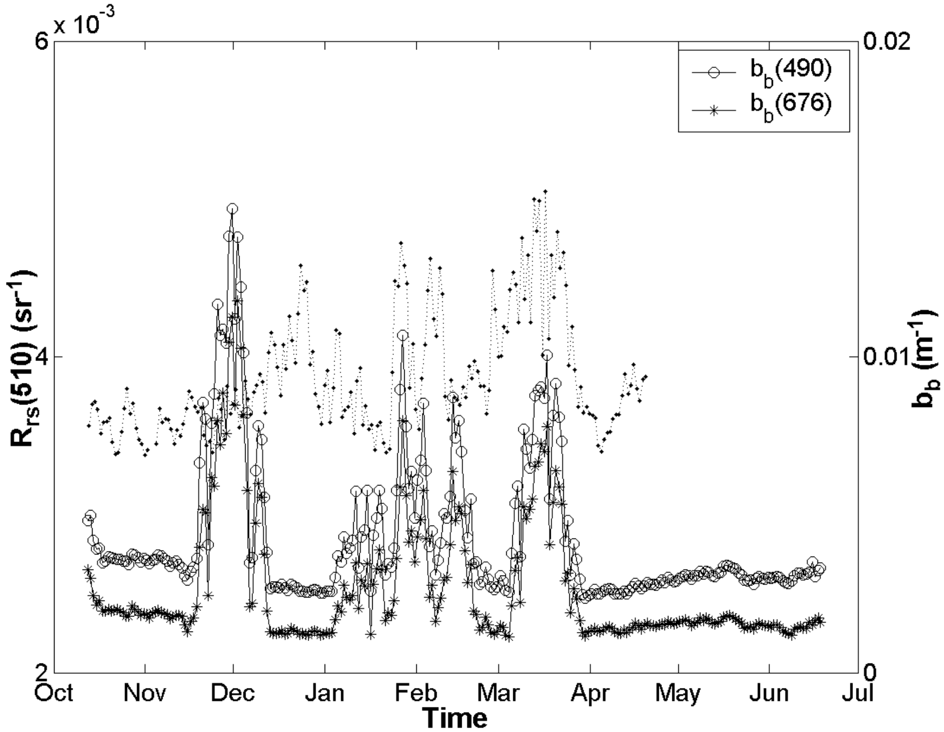

Figure 4.6: In situ backscatter data between October 2002 and June 2003, measured with a HOBI Labs, Inc. HS-2 illustrates the variability in particle density at EP1. At times this variability can also be seen in the R_{rs} data (dotted line, $R_{rs}(510)$ shown as an example) derived from mooring data.

4.4 CONCLUSIONS

Aside from setbacks related to vandalism (mainly tower and instrument controller theft), the two major mooring installations at 0°, 155°W and 2°S, 170°W are operating relatively well. The deployment of hyperspectral and backscatter instruments at both moorings is demonstrating significant potential and will better support validation efforts for ocean color missions.

This year alone we have preformed ~30 SPMR profiles, analyzed more than 2500 shipboard chlorophyll measurements, processed over 500 nutrient samples, processed 200 a* samples and collected close to 1000 HPLC samples. The program of cruise-based measurements as described above will continue on eight equatorial Pacific cruises during 2003-2004, with scheduled SeaWiFS LAC where applicable.

Table 4.1: Summary of cruises (in 2003) during which *in situ* data have been obtained by MBARI in support of SIMBIOS. All cruises were undertaken aboard the NOAA ship *Ka'imimoana*, with the exception of GP6-02-RB aboard the *Ronald H. Brown*. Meridional transects indicate the lines occupied by the ship. Along each line, CTD stations were performed approximately every degree of latitude from 8°N to 8°S, and every 0.5° between 3°N and 3°S. Measurements consisted of chlorophyll (Chl) plus nitrate, nitrite, phosphate and silicate (Nutrients) at 8 depths between 0 and 200m. On selected cruises, primary production (PP) and new production (NP) measurements were also made using ^{14}C and ^{15}N incubation techniques, respectively. Daily optical profiles were obtained using the Satlantic SeaWiFS Profiling Multispectral Radiometer (SPMR) where indicated.

Cruise ID	Dates	Meridional transects	Measurements
GP2-03-KA	24-Mar-03 to 28-Apr-03	95W and 110W	Chl, Nutrients, a*
GP3-03-KA	05-Jun-03 to 11-Jul-03	155W and 170W	Chl, NP, PP, Nutrients, SPMR, a*, HPLC
GP4-03-KA	13-Jul-03 to 11-Aug-03	165E and 180W	Chl, Nutrients, a*
GP5-03-KA	21-Aug-03 to 27-Sep-03	125W and 140W	Chl, Nutrients, a*
GP6-03-RB	11-Oct-03 to 12-Nov-03	95W and 110W	Chl, Nutrients, a*
GP7-03-KA	16-Oct-03 to 14-Nov-03	155W and 170W	Chl, NP, PP, Nutrients, SPMR, a*, HPLC
GP8-03-KA	16-Nov-03 to 14-Dec-03	165E and 180W	Chl, Nutrients, a*

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